Chapter 7

Resilient infrastructures for reducing urban flooding risks

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7.1 INTRODUCTION

The world's population living in urban areas is expected to increase from 55 to 68% by 2050 and the number of megacities with >10 million inhabitants from 33 to 43, with a faster pace of urbanisation in developing countries (United Nations, 2019). As the world continues to urbanize, sustainable development increasingly relies on the successful planning and management of urban growth, especially in hazard-prone regions. Natural hazards have heavily affected cities in recent years, for example, Hurricane Florence in 2018 and Harvey, Irma and Maria in the USA in 2017, the 2011 earthquake and tsunami in Japan, Cyclone Nargis in Sri Lanka in 2008, the Indian Ocean tsunami in 2004. The frequency and intensity of these phenomena seem also to be increasing due to climatic changes, with significant environmental, social and economic impacts (Stewart & Deng, 2014).

Natural catastrophes cause losses to people, properties and infrastructure according to their exposure and vulnerability. In particular, infrastructure represents a determining factor in limiting the impact of the events (Arrighi *et al.*, 2019; Garschagen *et al.*, 2016). Roads, for example, can provide access to

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emergency operation and evacuation, while if destroyed, entire areas can be isolated from support and aid (Arrighi *et al.*, 2020). In addition, infrastructure typically comprises various geographically extensive and interdependent systems (Chang, 2016); this interlinked nature results in cascading effects, i.e. disruptions in one system affect one or more other systems. For instance, the power supply system provides essential input (i.e. electricity) to transportation systems (e.g. to run electric trains), or water supply system (e.g. to run water pumps) (Pregnolato *et al.*, 2020). Consequently, the impact of natural catastrophes is often disproportionately large.

Modern cities are evidently complex and vulnerable environments, and at the same time a concentration of resources and wealth. When taking a long-term view, a resilient city is a system which includes the capability to withstand and bounce back from adverse events, and resilience is necessary for sustainable urban growth (Elmqvist *et al.*, 2019). As infrastructure is a core component of disaster risk reduction, the current challenge is to manage the resilient city's transformation process based on resilient infrastructure, thus enabling the city to provide services to its inhabitants even under adverse conditions (Pregnolato *et al.*, 2020).

In the context of highly vulnerable urban systems to hazards, adapting to reduce the harm is recognised as a primary need of the modern society (Aerts *et al.*, 2013). As adaptation is still to be completely defined and developed, strategies currently consist in 'learning by doing' and include all available options due to the uncertainties related to future climatic and socio-economic conditions. The implementation of adaptation measures involves decision-making and financing (Pregnolato & Dawson, 2018). At the stage of planning, various measures should be taken into account, alongside a range of decision time horizons (i.e. short-term, medium-term, and long-term) and uncertainties. By estimating the benefits from adaptation, innovative interventions related to infrastructure and urban planning could be seen as opportunities by investors and planners (Dawson *et al.*, 2015).

In recent years, a wide bulk of research has challenged practice and ways of thinking for the transformation of existing cities into adaptive and resilient environments; readers can refer to comprehensive works and reviews in published literature (e.g. Batty, 2013; Birkmann & Mechler, 2015; DEFRA, 2016). This chapter aims to discuss the role of infrastructure in resilient cities with a focus on adaptation strategies; it will review the main notions and concepts, and discuss a case study as proof of concept. It is intended to delineate a flood-wise city from an infrastructural point of view, illustrating advances in contemporary practice.

7.1.1 Definition of main terms

In literature, words like 'risk' and 'resilience' are becoming increasingly popular, with different interpretations. This chapter refers to the definitions of terms given below.

- Hazard: a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation (UNDRR, 2019).
- (National) Infrastructure: the fundamental facilities and systems serving a country, city, or other area, including the services and facilities necessary for its economy to function (O'Sullivan & Sheffrin, 2003).
- Reliability: a measure of the margin between demand and capacity, expressed in terms of probability of failure (UNDRR, 2019).
- Risk: the product of the probability of a hazard and the consequential damage, summed over all possible events, which is often quoted in terms of an expected annual damage (Hall *et al.*, 2003).
- Resilience: the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event (Cabinet Office, 2011).
- Adaptation: adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderate harm or exploit beneficial opportunities (IPCC, 2014).

7.2 REVIEW OF THE CONTEXT

7.2.1 Flooding hazard

The overflow of water that submerges land that is usually dry is a flood. Flooding is one of the most frequent and costliest hazards in many countries worldwide. This phenomenon can be caused by a range of triggers (Table 7.1), namely: (i) rivers, canals, mountain streams, or periodic water sources (generally, riverine flooding) – due to water exceeding the capacity of the water system; (ii) heavy rain (flash floods) – due to intense and sudden rainfall that overwhelms drainage and does not allow the soil to absorb the runoff; (iii) groundwater – due to prolonged rainfall that saturates the soil, often associated with high levels of surface water; (iv) sea and ocean (coastal floods) – due to sea water floods from estuaries and coastal lakes, usually associated with high tide levels, strong winds and high waves (storm surge); (v) drain and sewer – due to a blockage or failure within the drainage system, not necessarily attributed to weather; (vi) snowmelt – due to surface runoff associated with melting snow and ice; (vii) infrastructure – due to accidental failure of flood defense infrastructure (e.g. dams).

Flood risk combines the probability of flooding and the consequential damage (Hall *et al.*, 2003). Thus, flood risk depends upon the characteristic of the hazard trigger (usually represented by one or more intensity measures such as flood depth), the characteristics of the exposure (land use, assets value) and the vulnerability of the exposed elements to the hazard. Flood risk maps usually help to identify locations where there is potential of significant flood risk. These maps can be produced by means of simulation models. First, for a flood event of

Table 7.1 Different types of flood.

Flood Type	Cause	Duration	Damage
1. Riverine	Water exceeding the capacity of a body of water	Weeks to months	High
2. Flash flood	Intense sudden rainfall	Days to weeks	Medium-high
3. Groundwater	Prolonged rainfall	Weeks to months	Medium-high
4. Coastal	Storm surge	Weeks to months	High
5. Urban	Drainage system overwhelmed	Days to weeks	Medium-high
6. Snowmelt	Snow and ice melting	Weeks to months	Medium-high
7. Infrastructure failure	Accidental failure of e.g. dams	Days to weeks	High

reference, the runoff per catchment area is calculated, accounting for topographic features, by implementing a hydrologic model that converts precipitation to runoff. Next, a detailed hydraulic model is used in conjunction with the hydrologic model output to define a flow versus depth relationship for flood inundation extent (Merz *et al.*, 2010). There are a wide variety of models that account for varying degrees of physical complexity and offer subtly different solutions to a given problem (e.g. Neal *et al.*, 2012).

The damage estimation consists of evaluating costs and losses caused by floods to assets (e.g. buildings, infrastructure, environment) and human lives and health. Possible climatic changes could affect flood seasonality and intensity, e.g. cause changes in rainfall, snow accumulation, and snowmelt; the consequences of flooding could be also exacerbated by urbanization (e.g. increase of impermeable surfaces) and land-use (e.g. buildings on the floodplain). To reduce flood losses within current and future risks, communities need to increase their resilience to flood events, by enhancing the robustness of critical infrastructure (see Section 7.2.2) and developing cost-effective intervention strategies (see Section 7.2.3).

7.2.2 Infrastructure resilience from a system perspective

An infrastructure consists of a network of man-made systems and processes that function cooperatively and synergistically to produce and distribute essential goods or services. Modern infrastructure has evolved from collections of discrete physical components such as buildings and bridges, roads or emergency services into a tightly interconnected and interdependent physical, cyber and human components. Critical infrastructures are ‘those elements of national infrastructure the loss or compromise of which would result in major detrimental impact on the availability, delivery or integrity of essential services, leading to severe economic or social consequences or to loss of life' (CPNI, n.d.). The categorization of infrastructure varies but it typically includes the following sectors: communications, energy, transport, water, emergency services, financial services, government, food and health.

All infrastructures are subject to disruption due to different actions which could be internal to the system or external. Natural hazards such as floods, cyclones and earthquakes typically affect several infrastructure systems at the same time, resulting in damage to the infrastructure on a large scale. Man-made or technological hazards such as sabotage, explosions, fire and component failures alone usually do not result in widespread failure. Increasing complexity and interdependency of infrastructure systems can increase the risk of failure by propagating disruptions, so that the actual scale of the impact goes hugely beyond the area of the hazard. There are many examples (e.g. hurricane Katrina in USA 2005, tsunami in Indian Ocean region 2004, Christchurch earthquake 2010, Tohoku earthquake 2011) where their infrastructures were severely damaged resulting in wide-spread disruption to the societal functioning. In other cases (e.g. Eyjafjallajökull volcano 2011, heavy snow in the UK in early 2009, blackout in the Northeast USA in 2003) there was limited physical damage to the infrastructure system, but their functioning was disrupted, affecting the societal operations.

Predicting and managing the response of physical and human components of the infrastructure to the shocks and stresses is central to the functioning of society. Much of the infrastructure in Europe and in the USA is aged and in need of improvement as Tables 7.2 and 7.3 show; the grades are based on expert views of resilience, economic and social aspects, condition and capacity, leadership and other qualitative evidence.

The state of infrastructure in many other countries is not very different; some developing countries do not yet have adequate infrastructure while others regularly suffer from natural hazards including floods.

Table 7.2 State of the UK infrastructure (ICE, 2014).

Infrastructure Sector	Grade	Infrastructure Sector	Grade
Water and wastewater	B	Local transport	D–
Flood risk management	C–	Strategic transport networks (highways, air, ports)	B
Waste and resource management	C+	Energy	C–

Key: A – Fit for the future; B – Adequate for now; C – Requires attention; D – At risk; E – Unfit for purpose.

Table 7.3 State of the infrastructure in the USA (ASCE, 2017).

Infrastructure Sector	Grade	Infrastructure Sector	Grade
Drinking water	D	Ports	C+
Dams	D	Inland waterways	D
Levees	D	Roads	D
Wastewater	D+	Rail	B
Solid waste	C+	Bridges	C+
Hazardous waste	D+	Energy	D+

Key: A: Exceptional – fit for the future, B: Good – adequate for now, C: Mediocre – requires attention, D: Poor – at risk, F: Failing/critical – unfit for purpose.

7.2.2.1 Infrastructure risk and resilience

Typically, consequences of infrastructure failure can be grouped under three headings: (i) human – fatalities, injuries and psychological damage; (ii) economic – repair, replacement and compensation costs, traffic delay, re-routing and management costs, loss of business, reputation and share value; (iii) environmental – CO_2 emissions and pollutant release, energy costs. The UK summer floods in 2007 (Cabinet Office, 2008) are exemplary to demonstrate the scale of disruption to infrastructure and potential consequences: five water treatment works and over three hundred sewage treatment works were affected; the Mythe water treatment works in Gloucester alone resulted in cutting off the water supply to 350,000 people for 17 days; Walham substation came very close to failure which could have affected the electricity supply to nearly half a million people; Ulley Reservoir came close to being breached which could have resulted in the loss of life, damage to an important motorway, a major electricity substation and the gas network to Sheffield.

While each asset or component of infrastructure (e.g. power station or water pumping station) is designed to meet its performance requirements, predicting the knock-on consequences is not straightforward due to spatial distribution and interdependency of assets. The tools of scientific knowledge are well-established to model the demand and capacity of individual components or systems and arrive at probabilities of failure, i.e. reliability. To study the behaviour of geographically-distributed infrastructure, graph-theoretic tools are being increasingly used (Galvan & Agarwal, 2018). In a graph model of an infrastructure system, the nodes represent the components where the service is generated or delivered, the edges represent the connections between the components. The size of these networks can vary greatly depending upon the level of model required, e.g. national or city level. The effect of disruptions can be modelled by the loss of nodes or edges. A range of metrics are used to assess the consequences (Ouyang, 2014). For example, information centrality quantifies the consequences of removing a node in terms of the change in the efficiency of the network. The objective of such models is to identify the elements that are critical from the whole-system perspective, e.g. the failure of a few elements due to a localised hazard can result in loss of functionality over a much larger region. Such vulnerable elements may either be redesigned/strengthened, or protection and recovery measures may be put in place for rapidly restoring the infrastructure functionality. While such models are useful for planning and high-level decision-making, they are not intended to substitute physical models (e.g. hydraulic analysis of pipe networks or electric circuit analysis).

7.2.3 Adaptation strategies and adaptation benefits

Flood risk mitigation strategies can traditionally be classified into two main categories: structural and non-structural (Thampapillai & Musgrave, 1985). Structural measures are physical constructions and techniques aiming at reducing the flooding hazard; structural strategies modify the streamflow of rivers and channels leading to the reduction of the frequency and intensity of floods. Structural measures are further sub-classified into active and passive measures. Active structural measures modify the hydrograph involving mechanical or electrical systems (e.g. pumping), reducing and delaying the maximum peak discharge (e.g. on- and off-stream floodplain storages). The passive structural measures mitigate flooding by modifying the riverbed and its surroundings without involving mechanical or electrical systems (e.g. dams, levees, cleaning of the riverbed section from sediment, hydraulic bypass). Non-structural measures are procedures that do not require physical constructions; they consist of actions that lead to promoting knowledge, enforcing best practices, raising awareness and implementing strategic policies (e.g. flood early warning systems, land use regulations, flood insurance).

Over the last decade policy makers and stakeholders have been moving from the classical flood protection paradigm to the new concept of flood risk management. Specifically, urban drainage management has evolved significantly from a conventional ‘rapid disposal’ approach to a more integrated and sustainable ‘design with nature’ approach. Examples of this paradigm include new trending approaches worldwide, such as: Integrated Urban Water Management (IUWM), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SuDS), Sponge Cities and Low Impact Development (LID) (De Risi *et al.*, 2018).

7.2.3.1 Monetary and non-monetary benefits from adaptation

To assess which adaptation strategy needs to be applied, it is fundamental to be able to select among different alternatives. This selection requires the identification of the losses (i.e. the risk) associated with flood damages (Table 7.4). Damages caused by floods are generally classified into tangibles and intangibles (Nadal *et al.*, 2009).

Table 7.4 Classification of direct/indirect, tangible/intangible damages.

	Tangible Damages (Market Losses)	**Intangible Damages (Non-Market Losses)**
Direct	E.g. repair costs, replacement, cleaning costs, debris removal	E.g. casualties, injuries
Indirect	E.g. business interruption, rerouting	E.g. increase of inequalities

Analogously, losses due to flooding can be categorised into market versus non-market and direct versus indirect losses (De Risi *et al.*, 2018).

Direct market losses are the negative impacts of the disaster itself on goods and services and are generally determined using observable data (e.g. repair costs). Direct non-market losses are costs that are caused by the disaster itself but whose economic value cannot be readily quantified because they are not themselves traded on markets (e.g. anxiety, mental suffering, environment degradation). Indirect losses are not caused by the immediate disaster itself but rather by secondary effects. For example, damage to an infrastructure may cause business interruptions that continue far beyond the duration of the actual flooding itself. Therefore, flooding may cause indirect losses on economic activity outside of the flooded area as well, e.g. losses through supply chains during the 2011 flooding in Thailand impacted the electronics industry.

Engineers quantify risk in economic terms; therefore, they mainly focus on direct market losses. This quantification is conventionally performed convoluting the hazard, vulnerability and exposure models (De Risi *et al.*, 2013), and it is often referred to in terms of an Expected Annual Loss (EAL) (Hall *et al.*, 2003). Such integration in fact leads to the assessment of the EAL, which is the average annual loss expected for the asset at stake. The EAL is a key element for the selection of the best mitigation strategy.

A conventional tool adopted to select the best mitigation alternative is the Cost-Benefit Analysis (CBA). CBA is a commonly used method to compare the cost and benefit of different risk mitigation strategies over an investigated time interval (Dong & Frangopol, 2017). Engineers can quantify the cost of the mitigation strategy adopting any quantitative survey technique, and the benefit consisting of the reduction of EAL due to avoided costs after the application of the mitigation strategy. A CBA can be performed in many different ways. It has been recently demonstrated that Life Cycle Cost (LCC) and Return on Investment (ROI) are efficient decision variables for evaluating the financial feasibility and economic performance, respectively, of a set of flood mitigation strategies over time (De Risi *et al.*, 2018). In the same study it has also been demonstrated that LCC and ROI analyses yield identical rankings of mitigation alternatives only if the public policy or program being evaluated produces benefits only in the form of avoided costs. The presence of other types of benefits breaks the equivalence of LCC and ROI.

7.3 FLOOD-WISE USE OF URBAN INFRASTRUCTURE

Urban development represents an opportunity to link resilience and sustainability. Jingdezhen is an example of urbanised area and mid-size industrial city that is rapidly growing in the Jiangxi province in China (Figure 7.1). Jingdezhen lies at the interface between the Huangshan mountains in the north-west, and Poyang Lake, China's largest freshwater lake, in the south-east. The city is built in a low-lying area at the confluence of the Changjiang river with its two tributaries, the Nanhe and Xihe rivers. The Changjiang river drains an area of 6222 km^2 and has an average flow rate of 89 m^3/s, and high inter-annual and inter-seasonal variability (Hohai University, 2015). The city has a sub-tropical monsoon

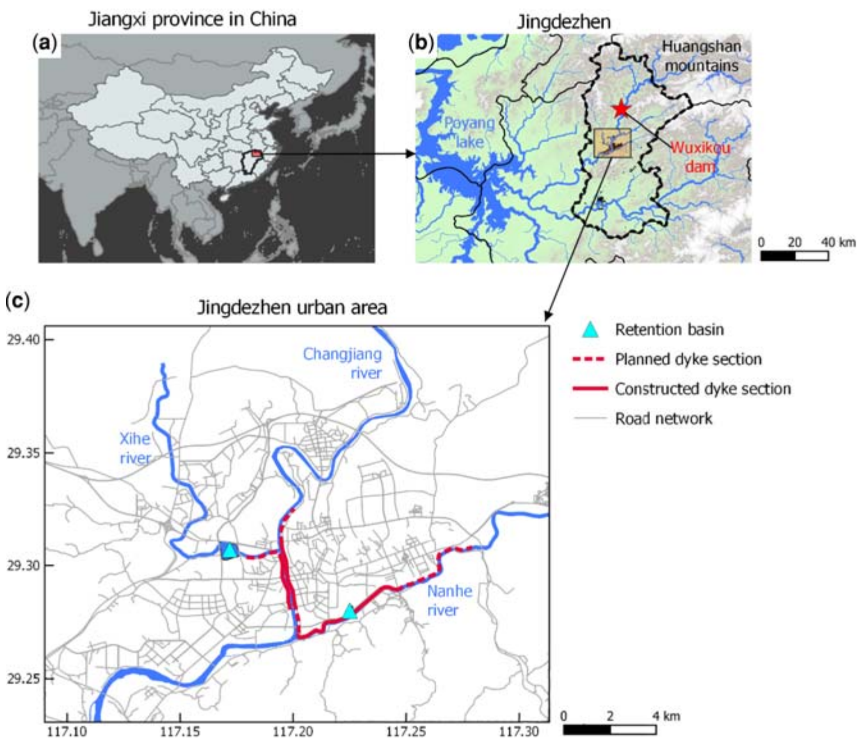

Figure 7.1 Map of (a) the study area showing, (b) the location of Wuxikou dam, approx. 40 km upstream of the city, and (c) levee sections to protect the city from a 1-in-20 year flood and two retention basins to store water from the Xihe and Nanhe tributaries. The road network is obtained from Open Street Map.

climate, characterised by warm temperatures and abundant rain. The average annual rainfall is 1800 mm, with half of the rainfall concentrated in the period between April and June (Hohai University, 2015). Between July and August, the city frequently experiences extreme rainfall events due to typhoons. The urban drainage infrastructure of the city consists of 26 km of pipes, but only 19% of it meets the standard for a one-year return period event. Issues such as bottleneck pipe sections, mild pipe gradients and insufficient outlets also contribute to the poor drainage capacity, and the rapid urbanisation is further increasing the pressure on the network (Wang *et al.*, 2018).

The city's population was approximately 480,000 in 2013 and it is predicted to increase to 1.2 million by 2050 (World Bank, 2013); this growing population is putting pressure on infrastructure, e.g. the water supply demand is forecasted to increase from 455,000 to 550,000 m^3/day between 2020 and 2030 (Artelia International, 2012). Its economy is growing at a rate of over 8% per year (World Bank, 2013) with regional GDP in 2017 corresponding to 87.8 billion Yuan, and ongoing urban growth would extend the urbanised area from 33 to 78 km^2 by 2030 (Hohai University, 2015). The growth planned by the Jingdezhen Master Plan 2012–2030 will include construction of new residential blocks, together with expanded water, drainage, road, and other lifeline networks throughout the city (Figures 7.2, 7.3(a) and (b)).

As a result of its topography, climate and infrastructure, the city is highly prone to flooding and has experienced frequent and severe floods throughout the years. Flooding in 1998 inundated over 90% of the urban area, in some places reaching a depth of 10 m, affecting 271,800 people and causing losses of over 2.3 billion Yuan (2.6% of regional GDP). In 2010, surface flooding from intense rain flooded an area of 9.1 km^2 up to a maximum depth of 2.8 m, with 2.96 billion (3.4% of regional GDP) in economic losses. The 2010 flooding caused interruptions to the power supply which interfered with the operation of drainage pumps that were being used to alleviate the flooding. The same occurred in 2016 when pumping stations had to be shut down during the flood due to power outages and the risk of collapse of an electricity pole near the Nanhe bridge that was still carrying traffic. A total of 119,700 people had to be evacuated, and the city sustained economic losses of 1.9 billion Yuan (Wang *et al.*, 2018). These events demonstrate how infrastructure can interact with hazards to amplify the consequences in urban areas.

7.3.1 Flood risk management in Jingdezhen

In 1998, the Jiangxi region authorities launched a flood risk management project to increase the flood protection beyond the 1-in-5-year flood standard at that time. The objective is to provide 1-in-100 level flood protection by 2050, with expected annual losses limited to 0.5% of GDP, and to ensure no fatalities due to floods. Structural measures were designed to protect up to a 1-in-50 year

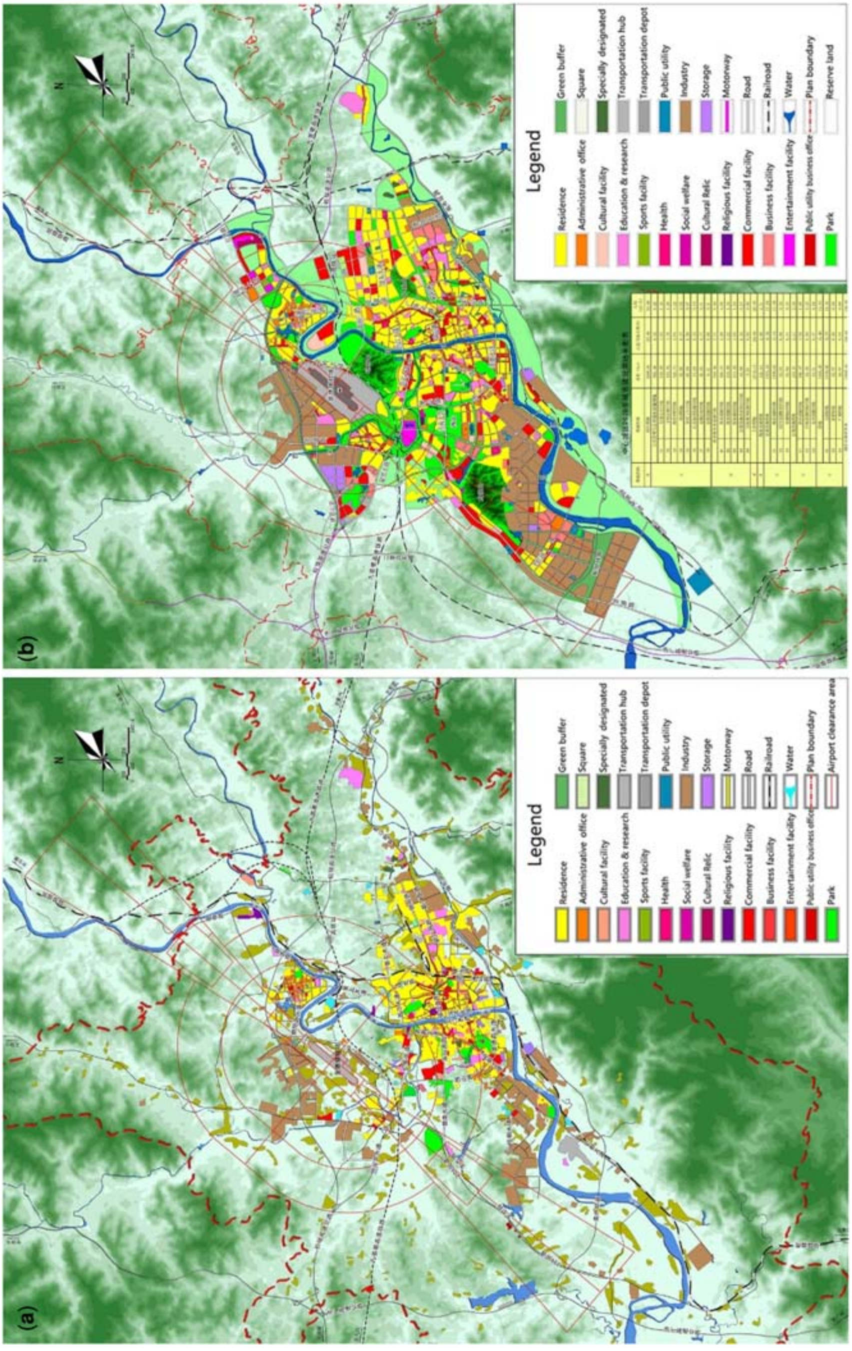

Figure 7.2 Land use in (a) 2010 and land use planning in (b) 2030 for the city of Jingdezhen, according to Jingdezhen Master Plan (2012–2030).

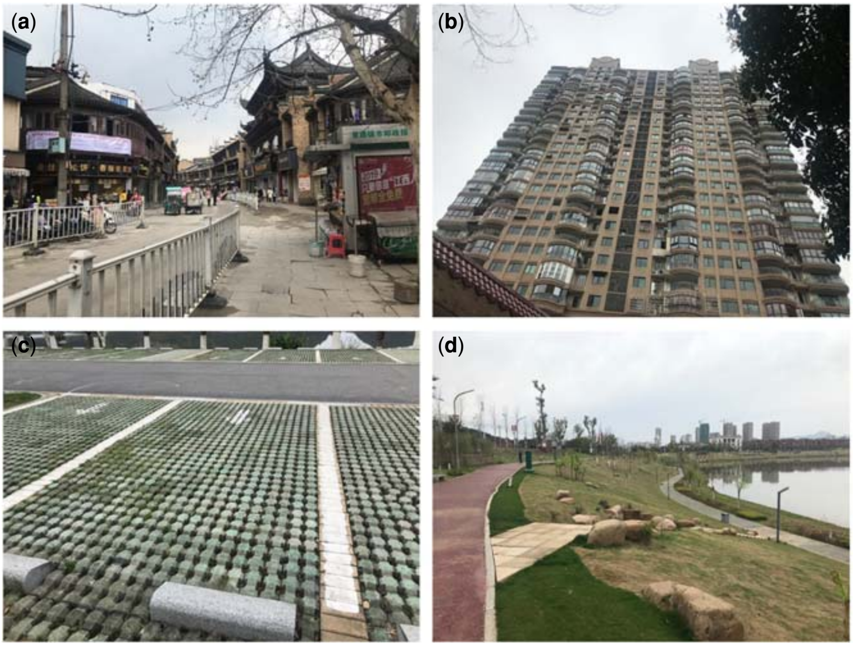

Figure 7.3 Jingdezhen's snapshots: (a) the Old Town, with the characteristic architecture and low-rise buildings; (b) the new development consists in high-rise buildings; (c) example of SUDs (permeable pavement) in parking areas; (d) greenery and pedestrian walkway, as part of the construction of the levee section.

flood level, and these include: (a) construction of the Wuxikou dam on the Changjiang river, 40 km upstream of the city (Figure 7.1(b)); (b) the construction of 58 km of dikes to protect the urban centre (Figure 7.1(c)); (c) drainage improvements and urban retention basins to manage stormwater. Further non-structural measures were planned to manage the flooding up to a 1-in-100 flood, including enabling the city to better evacuate and recover in the event of a flood (Figure 7.3(c) and (d)).

The Wuxikou dam on the Changjiang river is located 40 km upstream of the city. The dam (46 m high, 538 m long) has a total storage capacity of 427 million m^3 and an installed hydropower generation capacity of 32 MW. The dam is designed to protect the city up to a 1-in-50-year flood. In addition to flood mitigation, it is expected to provide added benefits by ensuring security of water supply, to satisfy the forecasted increase of the demand. The current abstraction point on the river is therefore being moved upstream to the reservoir, from which water will be channelled through a separate pipe to the city.

The levees are designed to protect the city up to a 1-in-20-year flood (Hohai University, 2015). To provide continued access to the river by the city inhabitants, the levees include stairs that lead to a green area along the river, with pedestrian walkways, play areas, and diverse vegetation (Figure 7.3(d)). The construction of the levees also includes 16 pumping stations that drain the flood waters and limit the extent of damage in case of flooding.

Drainage improvements include the construction of separated stormwater and foul water sewers in newly developed parts of the city, and an upgrade of the network in the old part of the city to have the capacity to drain a 1-in-20 year, 24-hour-duration, rainfall event. Urban stormwater management capacity has also been increased by constructing two large water retention areas, the Changnan Lake and Laonanhe retention basin in the low-lying areas of the city, to increase storage capacity from the two tributaries. Laonanhe retention basin has a total surface area of over 61,200 m^2 and a total storage depth of 4.5 m. It will include leisure space with playgrounds and a pleasant waterfront area, paved with permeable bricks and stone to enable infiltration of rainwater. Vegetated ditches will contribute to cleaning the rainwater that flows to the lake.

Non-structural measures are also being carried out to improve flood management capability. This includes training local decision makers, conducting visits to observe and learn from best-practice in other cities in China and abroad, conducting an education campaign to raise awareness within the local population, updating the forecasting system to include the influence of the operation of the Wuxikou dam, and including risks associated with dam or levee break into the existing emergency response plan.

7.3.2 Costs and benefits from adaptation measures

The total cost of the flood protection project is 513.7 million US$, which corresponds to approximately 4% of the regional GDP in 2017. Of this, 114.9 million (22%) is used for constructing the dam, 384.6 million (75%) for implementing the resettlement action plan, and 9.4 million (2%) for additional non-structural mitigation measures. Resettlement costs thus represent most of the project cost: the construction of the levees means displacing over 2000 homes and over 300 businesses from the flood prone riverbanks and resettling them to other parts of the city, while building the dam involves resettling 9800 people from villages within the reservoir area (Artelia International, 2012). Funding for the project comes from a partnership funding involving the local government (41.1%), supplemented by the regional (9.4%) and national government (30%), together with a loan from the World Bank (19.5%).

For the Wuxikou dam, eight scenarios were modelled to assess the dam effect in terms of flood alleviation in the future (2030), as compared to the present day (2010) (Figure 7.4). Four maps (Figure 7.4(a), (c), (e) and (g)) simulate various return periods, land use, drainage network, and embankment for the present day (2010). The other four maps (Figure 7.4(b), (d), (f) and (h)) are for a 2030 land use plan, while the drainage network and embankment do not change with respect to 2010.

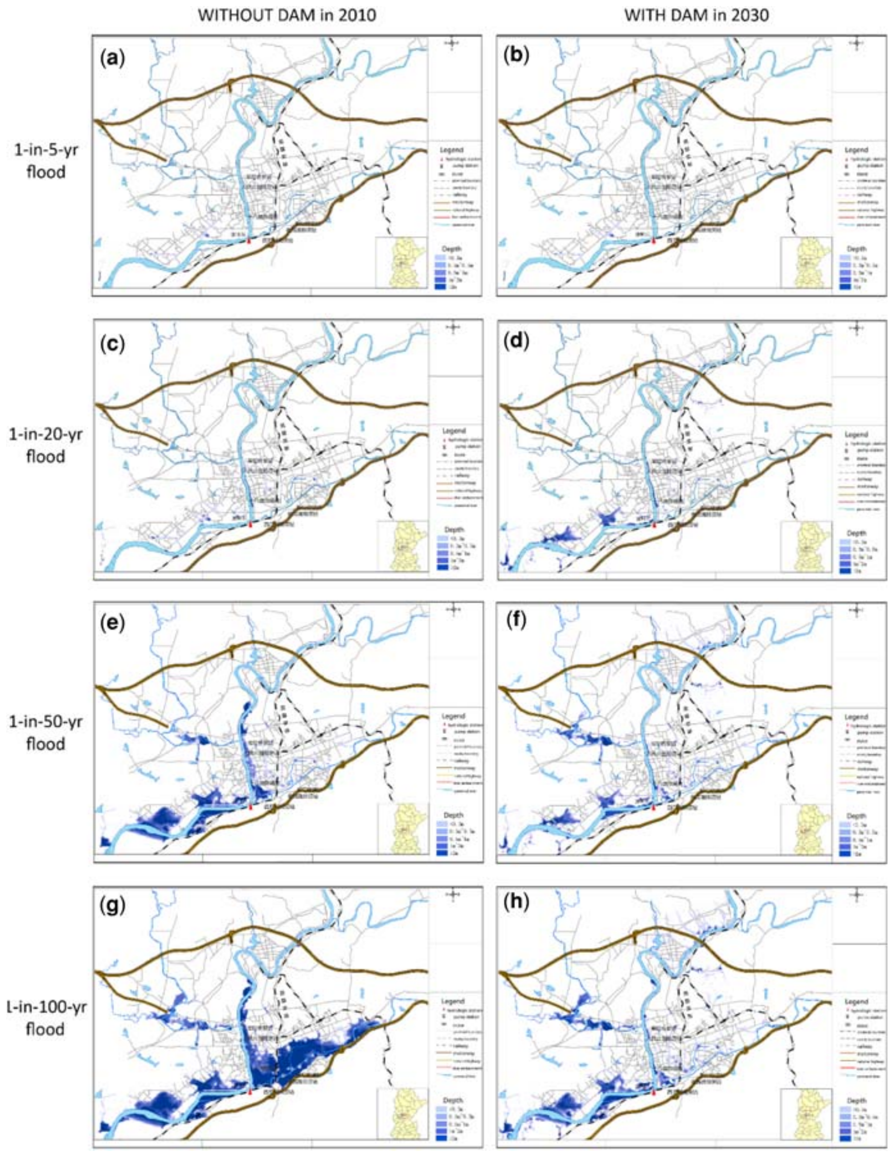

Figure 7.4 Modelled flood maps for present (2010) and future (2030) scenarios: (a/b) 1-in-a-five-year flood event without/with Wuxikou dam; (c/d) 1-in-a-20-year flood event without/with Wuxikou dam; (e/f) 1-in-a-50-year flood event without/with Wuxikou dam; (g/h) 1-in-a-100-year flood event without/with Wuxikou dam. 2030 scenarios include urban development according to land use planning.

With respect to the 1-in-a-five-year flood event, the flood footprint increased by +67% from the current and with respect to the 1-in-a-20-year flood event, the flood footprint increased by +69%. On the contrary, with respect to the 1-in-a-50-year flood event, the flood footprint decreased by 42% and with respect to the 1-in-a-100-year flood event, the flood footprint reduced by –36% (Figure 7.5 and Table 7.5).

The interventions are also expected to bring other improvements in the quality of life in the city. Green areas along the levees and urban storage areas will provide public leisure space and access to nature which improves wellbeing. The construction of the dam will provide a reliable source of water to mitigate shortages. Buildings along the riverfront that were exposed to risks of erosion of the riverbanks were resettled to new areas away from the river, providing safer living conditions to the residents. The key objectives that underly flood management efforts are indeed to safeguard social stability and to promote stable economic development.

The embankment of the urban reach of Changjiang River is designed to withstand the shocks of 1-in-50-year flood with the Wuxikou Dam; several sections of the embankment should be raised if using the flood protection standard of 1-in-100-years. However, raising the existing embankment would lead to high costs due to the engineering quantity and urban planning (e.g. resettling the population), while non-structural measures were proven to reduce the total loss if supplemented to relatively low protection standards. Therefore, the combination of structural (levees, dam, drainage upgrades and retention basins) and non-structural (evacuation, insurance, raising awareness) measures was found to be the most cost-effective way of limiting future damage.

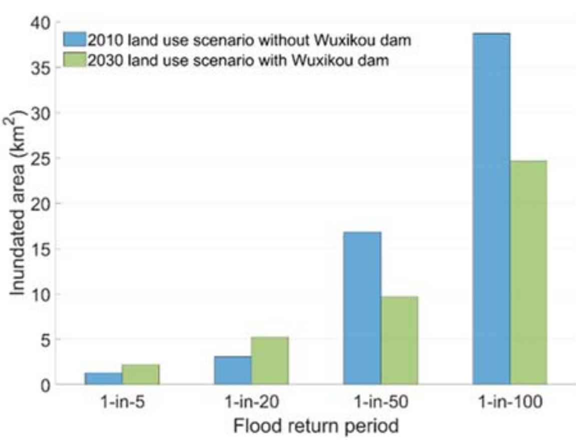

Figure 7.5 Inundated area (km^2) per flood return period and scenario.

Table 7.5 Modelled flood depths and footprints for the eight scenarios (2010 without dam/2030 with dam).

Return Period	Area in Different Depth (km^2)					Total Flood Area (km^2)
	<0.5 m	0.5–1 m	1–2 m	2–3 m	>3 m	
Flood area in 2010 scenarios						
1-in-5-year	1.070	0.182	0.056	0.001	–	1.309
1-in-20-year	2.419	0.367	0.223	0.037	0.041	3.087
1-in-50-year	4.569	2.544	3.692	2.698	3.241	16.744
1-in-100-year	6.369	4.514	8.235	6.683	12.917	38.718
Flood area in 2030 scenarios						
1-in-5-year	1.777	0.163	0.142	0.070	0.046	2.198
1-in-20-year	3.653	0.802	0.444	0.180	0.147	5.226
1-in-50-year	4.826	1.668	1.326	1.380	0.486	9.686
1-in-100-year	7.289	5.240	5.572	3.746	2.831	24.678

7.4 DISCUSSION

Flood losses are expected to increase due to climatic changes and urbanization. The case study of Jingdezhen presented an example of an ongoing flood risk management project for enhancing urban resilience and reducing the impacts of flooding in cities through infrastructure. The combined approach using structural and non-structural measures reflects the recent shift in thinking and practice, which has moved away from a flood control approach, towards increased flood risk management.

Strategies that are being implemented combine increasing flood protection with an improved ability to cope with flooding. As the reservoir, levees, and retention lakes reduce the frequency of flooding, other measures (e.g. education) will be essential to maintain the awareness and preparedness of the population to ensure that the city is able to cope when a flood does occur. In a context of remarkable urban growth, adaptation (structural) measures that target low-probability high-impact flooding events (i.e. 1-in-50/1-in-100-year events) guarantee a higher return of the initial investment. For less extreme events (i.e. 1-in-5/1-in-20-year events), the high costs required are less justified because, for example, the inundated area is not reduced for the 2030 period. However, future scenarios included planned urban development which increases urban runoff; this runoff is tackled by non-structural measures for high-probability events. This approach recognises that floods cannot be entirely prevented and aims to promote a philosophy of living with floods.

7.4.1 Next frontier of research

The combination of structural and non-structural measures promotes cost-effective planning for enhancing urban resilience. These measures target flood alleviation as the main benefit but encompass a wider range of positive effects. For example, the Laonanhe retention basin improved the urban quality of Jingdezhen by including a leisure space with playgrounds and a public waterfront area. However, no method exists in current practice and research to account for such co-benefits. Future research could investigate about how to include co-benefits from adaptation measures into existing economic appraisal (EAL, ROI, etc.).

There is increasing research effort on identifying interdependencies between different infrastructure systems. This is expected to lead to scenarios that have the potential to be critical from a system-of-systems perspective. These can then be used for designing appropriate protection measures from floods and/or preparing rapid recovery plans. Infrastructure improvements could indeed form part of a city-wide resilience strategy, to ensure that existing and newly constructed lifelines are able to cope in the event of a flood. For example, isolating and waterproofing the electricity supply to ensure continued operation during floods; identifying priority road sections and junctions that could be strengthened to maintain connectivity of the city during and after flooding; or better understanding the criticality of the regional rail, road, and power transmission grids, so that new construction can be combined with reducing the vulnerability of the networks as a whole.

7.5 CONCLUSION

Flooding risk to cities has to be managed through resilient and sustainable planning, especially in fast-developing areas. The planning of a flood-wise city requires understanding of the potential consequences from a hazard, designing for structural measures to reduce these consequences and preparing the community to withstand impact. The city of Jingdezhen showed how structural (e.g. dikes, levees) and non-structural measures (e.g. preparedness) could be successfully combined for reducing flooding risk for future scenarios. Future research could follow up on how to integrate adaptation co-benefits into current economic appraisal of adaptation measures and how to address resilience from a system-of-system perspective.

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